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Potential market for small-scale gasifiers in rural areas of developing countries

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Abstract

This thesis report assesses the potential market for small-scale gasifiers in rural areas of developing countries and regions. Biomass is already widely used in these areas for energetic purpose, giving gasification an interesting niche market for remote electricity production. Success factors include a high reliability, an efficient biomass supply chain and sufficient local electricity needs. Suitable fuel for a gasifier must be available at low cost, which could be wood harvested locally or agricultural residues such as rice husks or nut shells.

A good potential for gasifiers fueled by wood has been identified in Eastern Africa, based on FAO's wood supply-demand models. South-East Asia and South America produce a lot of agricultural residues suitable for gasification. However, the electrification rate in South America is already high, which reduces considerably the interest for small-scale decentralized electricity production.

Taking into account all these parameters, the most promising countries are Nigeria, India, Myanmar and Indonesia. Thailand, Cambodia and the Philippines also offer opportunities in the rice and sugar industries, while the wood industry in Cameroon shall deserve a deeper investigation.

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1 Introduction

This study originates from a mission that the author has carried out during an internship at Enea Consulting, France. The client was Xylowatt - a company developing gasification systems functioning with various types of waste biomass feedstocks. One of their projects focuses on the development of one standardized 50-kW$_e$ gasifier design and one 200-kW$_e$ gasifier, aimed to serve rural areas where there are biomass resources available and the local population is in need for electrification. When the hereby presented work was initiated, the client had already carried out a specific field study in India which concluded that the market was considerable.

Xylowatt and their gasification technology have no intention to compete against small hydropower plants, but consider that they should be competitive against photovoltaics, claiming a lower investment cost. They are aware that competitors, such as Husk Power Systems or Ankur Technologies, are already implemented for over 30 years, providing gasifiers of the same range of power output. However, the existing systems have poor operational performance and a low reliability. Therefore, Xylowatt believe that there is a market for their products, which they consider to be more reliable and robust.

At the moment of the study, the gasifiers were still at the development phase, and so was the business model. For example, the idea of supplying an open-source technology has been assessed by other consultants from the author's team. The goal was to design a technology simple enough to be built locally.

The author's task has primarily focused on the assessment of the potential market for Xylowatt's products in rural areas of the developing world, country by country, and to determine some countries or regions that deserve to be investigated more deeply.

At the moment of the finalization of this report, it seems that Xylowatt's strategy has shifted and their website [1] does not seem to mention anything about the developing world nor the open-source license. However, it still provides a description of their product, the Notar © gasifier [1], shown in Figure 1.

This thesis is built in 3 major parts. First, an insight of the challenges to the access to electricity in rural areas in developing countries is given. Then, a short description of the gasification technology and its applications is provided, including the comparison of different types of feedstock that can typically be used in the targeted areas. Finally, the potential market for gasifiers in some representative areas of the developing world is assessed, using several methodologies and summing up the results by identifying and quantifying the most promising markets.

The Notar © technology [1]

Xylowatt's gasifier is a multi-level design, allowing to physically separate the 3 main phases of the gasification process (pyrolysis, combustion, reduction). A gas-processing unit is integrated in the design. The syngas can then be used to produce electricity or heat in a separate energy conversion unit, depending on the user's needs.

For the analysis of the potential market applications in this study the author applies the general data provided by Xylowatt about their gasifier units, by only using the overall output parameters and without scrutinizing in detail neither the technology itself nor the claimed performance.

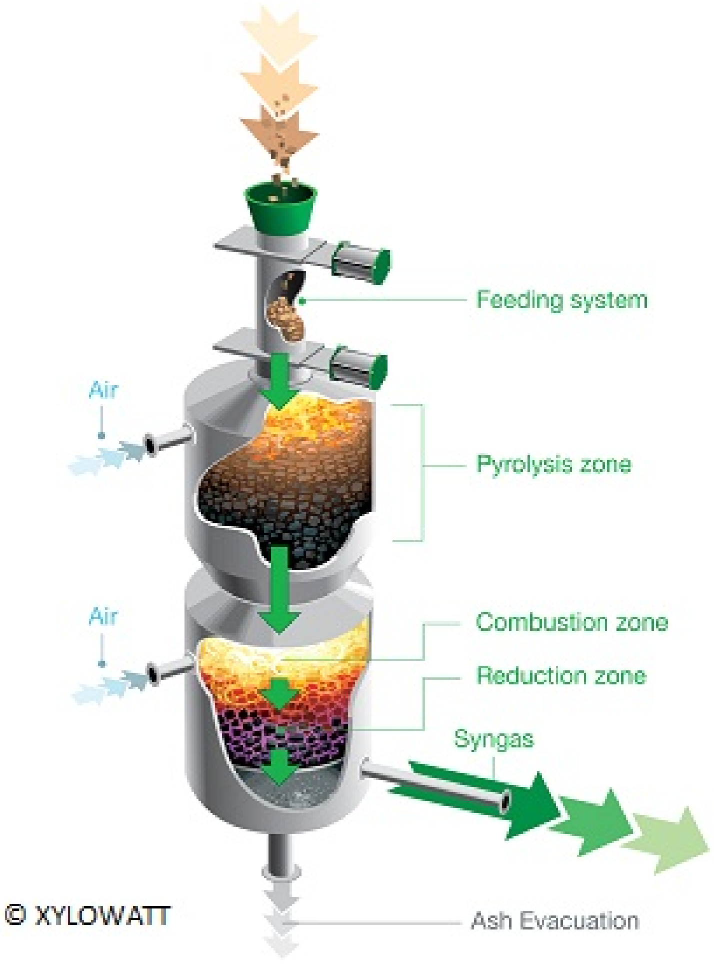

Figure 1: The Notar © gasification technology (taken from [1])

2 Access to electricity in rural areas in developing countries

2.1 Global challenges for access to electricity and biomass utilization

According to an IPCC report [2], 10,2 % of the annual global primary energy supply is based on biomass, which amounts to 50,3 EJ per year. Between 37 to 43 EJ, i.e. around 80% of the primary energy supplied by biomass, consist of low-efficiency traditional biomass use: cooking, space-heating and lighting usually by means of direct combustion.

Figure 2 shows the shares of different types of biomass in the global biomass primary energy supply.

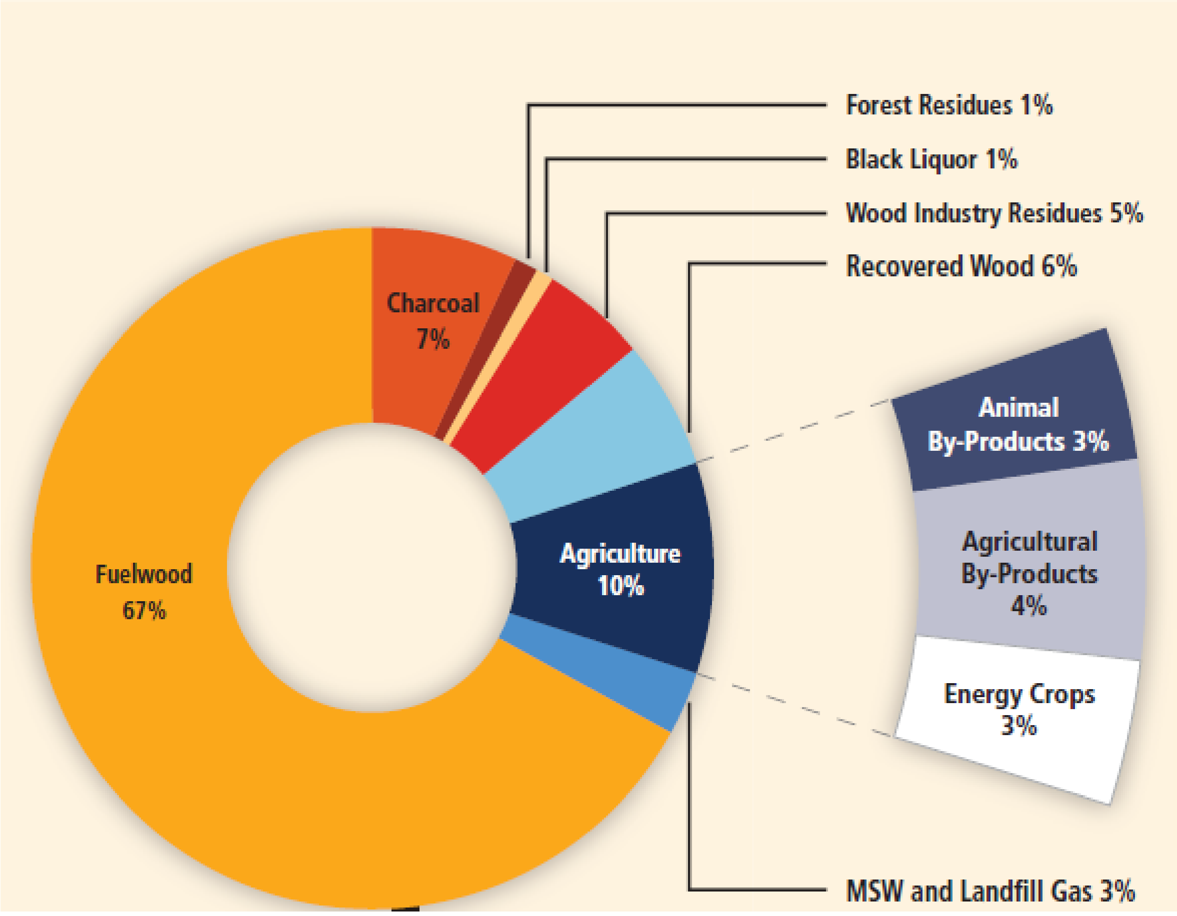

Figure 2: Shares of global primary biomass sources for energy (from [2])

According to IEA's World Energy Outlook [3], 2,6 billion people worldwide rely on traditional use of biomass for cooking, which represents 49% of the population of developing countries and 38% of the global population. This is most critical in Africa and developing Asia, where respectively 68% and 51% of the population rely on traditional use of biomass for cooking.

Besides, in 2009, 1.3 billion people had no access to electricity, which represents 19.5% of the global population and 25% of the population of developing countries. With an electrification rate of only 42%, Africa is the most critical area in terms of access to electricity.

There is a big difference between electrification rates in rural and urban areas. In Africa, only 25% of the rural population is electrified, against 69% of the urban population. The situation is better in Asia, with electrification rates of 73% and 94% in rural and urban areas, respectively.

In the IEA's World Energy Outlook 2010 [3], the additional power generation required in order to fulfil universal electricity access by 2030 was calculated. Results are summarized in Table 1.

TWh	Mini-grid	Off-grid	On-grid	Total
Africa (SSA)	187	80	195	462
India	112	48	85	245
Rest of Asia	94	40	87	221

Table 1: Additional annual power generation requirements for universal electricity access by 2030 [3]

The IRENA (International Renewable Energy Agency) estimated that the technical potential for power generation from biomass, in Africa, amounts to 2600 TWh per year, mostly in Central and Eastern Africa [4]. In Benin alone, the electrical power capacity that could be generated and from the gasification of agricultural wastes is estimated to 766 MW_e .

Therefore, at the continent level , the required additional power generation in Africa (462 TWh) can theoretically be met by using only 18% of the biomass potential (2600 TWh). However, this does not take into account the necessary match between the local availability of resources and people's needs.

2.2 Advantages of gasification for decentralized power generation

The general figures provided in chapter 2.1 raise several challenges.

2.2.1 A better use of the biomass resources

Traditional biomass uses have a very poor thermal efficiency, estimated at around 10-20% [2]. Therefore, there is room for improvement of the use of biomass resources, which can lead to more sustainable harvesting schemes and prevent deforestation and desertification.

Besides, traditional uses of biomass have sanitary impacts. According to the World Health Organization, "more than 1,45 million people die prematurely each year from household pollution due to inefficient biomass combustion" [5].

Land degradation and local air pollution are also very important aspects, as well as risks inherent to biomass fuel collection (e.g. snake bites, human assaults…).

Biomass gasification may be part of the solution to all these issues. Of course, it seems complicated to provide the output gas for cooking purposes. In order to provide gas bottles to be used in modern gas cooking stoves, this would require compressing, separating and liquefying the gases, bottling them, organizing a supply chain for its distribution, and installing suitable cooking equipment in households. The investment cost required to build such infrastructure cannot be supported by a single company and does not seem to be viable in the short to medium term.However, the main advantage of a biomass gasification project in this perspective is that it would require a well-thought and managed biomass supply chain to secure long-term operation of the gasifier. Therefore, it can be a good reason to put in place some biomass management policies at a local level.

2.2.2 Providing electricity to remote population

Access to electricity is necessary to fight poverty. A report from the United Nations Development Programme (UNDP), the World Bank and the Energy Sector Management Assistance Programme highlighted the central role that access to modern energy services (including electricity) plays in order to achieve the Millennium Development Goals (MDG), even though none of the MDG deals specifically with energy [6]. This report deals with all "improved energy services", which includes "modern cooking fuels, improved cooking stoves, increased sustainable biomass production, and expanded access to electricity and mechanical power" [6].

Our work focuses on small-scale electricity production from biomass, which can be an answer to both the issue of electrification and the mismanagement of biomass resources.

2.3 Main barriers

2.3.1 Financial barrier

To be successful, energy projects must be profitable, which is not the case for advanced gasification technologies yet. For example, Dantas *et al.* calculated that from a purely financial point of view, biomass integrated gasification coupled with a gas turbine and combined cycle (BIG-GTCC) require a cost reduction of 48% to become competitive against conventional bagasse burning plants [7].

However, the technology involved in Xylowatt's product is supposed to be simple, reliable and cost-effective. As the project was still in development phase at the moment of the study, no cost data is available. It should be noted anyway that there are already competitors, particularly in India. Reference [8] lists 18 manufacturers in India only, providing downdraft or updraft gasifiers for thermal purpose only or for power generation as well. This tends to prove that small-scale gasification is already market-ready.

2.3.2 Operational barriers

Even if it is designed to be very simple, a gasifier needs qualified people to make it work. Such persons might be hard to find in remote rural areas. In addition, such energy projects have a low probability of success if they are not carried by local companies or institutions. A gasifier installed by a foreign company, for example as part of a development program, is not likely to be "adopted" by the local people and will have a short life expectancy. The Open-Source business model briefly described in the Introduction might be an answer to this issue, by involving local businesses in the process and creating value locally.

In addition, a commercial operation should be preferred. If the end-users pay for the service, they are generally more careful to the benefits that they can get from it. Contreras [9] uses the capacity to pay for electricity as one of the main drivers for the assessment of electrification projects (see also 2.4.1).

2.4 Energy needs in rural areas of developing countries

2.4.1 Electricity consumption of a typical village in a developing country

Before doing a market study, it is necessary to know the actual need for electricity in rural areas of developing countries. Indeed, one of the commercial targets is unelectrified rural communities, so we need to understand what kind of communities could benefit from Xylowatt's gasifier designs: how many residents, typical load curves, etc.

A model of the electricity consumption of a village in Senegal has been developed by Contreras [9], based on a real project. Their purpose was to identify economic criteria, like the "willingness to pay for electricity", that can make photovoltaic projects profitable without subsidies, which explains that the following costs may seem high.

It consists of a village of 500 inhabitants, which is equivalent to about 50 households. The population is divided in four categories, according to their capacity to pay for electricity. The poorest category is made of households that can afford some lighting (3 bulbs) and a radio player and represent 25% of the population, able to pay about 4 € per month for electricity. With twice higher budget, the second category (28% of the population) could afford 5 light bulbs and a small TV set. The third category would be able to pay around 15 € and add a larger TV set and a fan. Finally, the richest category, which represents only 14% of the population, could spend 24 € per month for electricity which would allow them to add a fridge or other electrical appliances to their homes.

In addition to those domestic uses, the study considers the electric consumption of some community services: a school, a nursery, an administrative office, telecom equipment, a mosque and some public lighting, as well as four revenue-making activities: a carpenter workshop, a mill and two shops.

Using all this input data, Contreras [9] simulated a typical electric load curve for the village as shown in Figure 3.

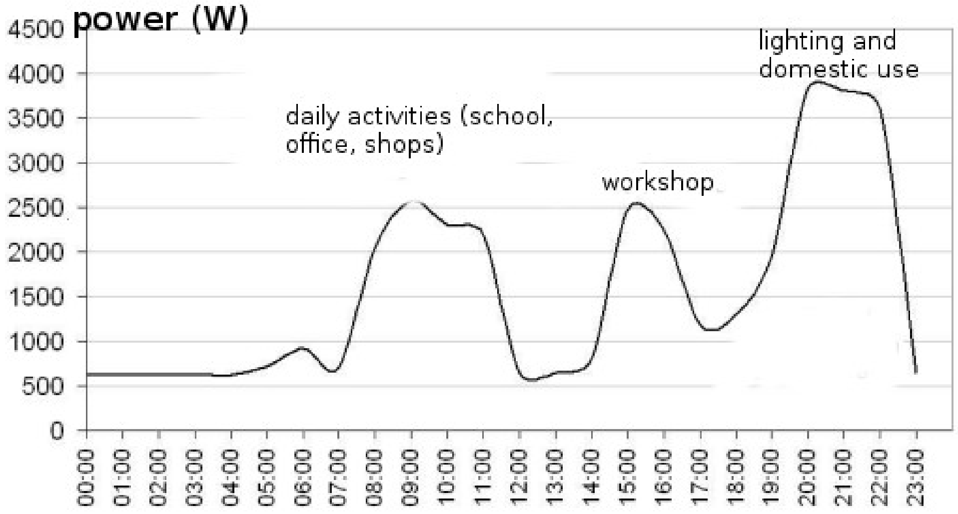

Figure 3: Typical daily load curve for a village in Senegal (adapted from [9])

According to reference [9], the electric load in the village is very variable. From a base load of about 600 W, it goes up to almost 4 kW in the evening, when lighting and domestic appliances are in use.

Daily electricity consumption are also calculated by Contreras [9]. Average electricity consumption can be estimated from those figures, as shown in Table 2.

	Per village per day, in kWh	**Per village per year, in kWh**	**Per person, per year, in kWh**
Domestic usage	3.42	1246	2.5
Community usage	5.90	2153	4.3
Total	**9.31**	**3399**	**6.8**

Table 2: Average electricity consumption of a village in Senegal (from [9]Error! Not a valid bookmark self-reference.**)**

Their model takes into account the custom in the area under study, where productive activities (in this model, a carpenter workshop) are carried during 2 hours in the morning and 2 hours in the afternoon. The rest of the activity (shops, offices, school) is done mostly in the morning.

This variability must be taken into account when choosing among different power generation technologies. Indeed, it means that there is a real challenge for meeting the power demand: the power generation must match the demand, while remote areas cannot generally afford complex network regulation or qualified technicians to run the plant. Therefore, the technology chosen must be at the same time flexible and easy to use.

At first sight, one way of dealing with this issue is to add batteries to the installation. However, this increases the investment costs of the project. As gasification projects already are capital-intensive, adding batteries would decrease even more their competitiveness and their profitability.

2.4.2 Energy needs of rural industries

One 50- or 200-kW gasification unit might be oversized for just one village or rural city, and building an electrical network between several villages in sparse rural areas is capital-intensive. Therefore, one factor success for such a project is to have some small businesses or industrial plants in the area. The benefit is two-fold : first, it provides a stable demand at a different time than domestic demand; second, local agricultural industries may provide their residues as fuel for the power plant.

This second point is essential. If there is a local agricultural industrial plant (e.g. a rice mill), there are multiple benefits for the whole society:

- The plant can sell its residues and hence value them
- There is no need to put in place a biomass supply scheme, as the residues are already gathered in one location
- There is no competition for resource or land use
- The disposal issue is solved for the residue used as fuel.

A few types of industry were identified as interesting for gasification project, because they can be at the same time producers of residue, i.e. fuel, and consumer of electricity. They are presented and investigated in detail in chapter 4.5.

3 Gasification from a technological point of view

The purpose of this chapter is to give very general information on the gasification process. As the technological aspect of gasification was not investigated in the study, it is not developed here (see also Introduction).

However, some facts about the different types of fuels that are considered further in this report are given and explained in paragraph 3.2.

3.1 What is gasification

The gasification is a process that converts a solid (usually composed of carbon, hydrogen and oxygen) into combustible gases, inert gases and other emissions. It is achieved by introducing a specific limited amount of oxidizing agent: air, oxygen or steam at high temperature.

The gasification process can be broken down in several distinct steps. First, there is the drying phase during which water is removed from the solid fuel. This can be achieved using different methods, such as those involving cavities, capillaries or heat coming from the combustion in order to release water from the fuel by evaporation. The wetter the fuel is, the more energy is required in the drying process.

Next, the fuel undergoes an endothermic decomposition which therefore requires a heat supply. This heat comes from the combustion and makes the ignition self-sustained. The solid fuel turns into volatile gases such as CO, CO_2, CH_4, NH_3 and H_2 and tars in a temperature range from 450K to 1100K. Tars are a solid residue, composed mainly of elemental carbon and ash, which is left after the pyrolysis.

The next step is the combustion process in which an oxidizing agent is supplied in deficit. During that stage, gases such as H_2, CO and CH_4 are consumed with oxygen and provide heat for the previous steps. All of these reactions will lead to the release of water and carbon dioxide. Combustion of char can also be noticed at this stage, leading to the release of CO_2 and CO, as well as CH_4.

The final sub-process is the reduction of the char into the product gas in absence of oxygen. The product gases are mainly H_2, H_2O, CO and CO_2. Several factors are important during this sub-process, such as the time of residence of the char in the gasifier, along with the temperature and reactivity of the char.

3.2 Suitable types of fuels

Choosing an appropriate fuel to feed a gasifier is of great importance. It has impacts on the composition of the gas produced and hence on its heating value, but also on the operation of the gasifier. For example, higher concentrations of potassium in the fuel lead to agglomeration issues during thermal conversion [10].

The two types of biomass resources that are investigated in this report are wood resources and agricultural wastes.

3.2.1 Gasification of hardwood

3.2.1.1 Efficiency of the gasification of wood

In [11], wood chips were used as fuel for a laboratory-scale downdraft gasifier using air as the gasification agent, with good results. Those chips were forest industry residues. In their solid form, these chips had a

HHV of 20,5 MJ.kg^{-1} , and their gasification led to the production of gas with a LHV of 5,6 MJ.m^{-3} with a yield of 60% [1]. According to the authors, these good results stem from the high calorific value of the chips, their low ash content and the fact that they are suitably sized. They also benefit from a low moisture and hence a high LHV of about 19,3 MJ.kg^{-1} (see calculation in Table 3).

HHV		20,5	MJ/kg
Moisture F		7,5	% of fuel mass
Combined H2O		43,7	% of fuel mass
->	H2	4,9	% of fuel mass
->	O	38,8	% of fuel mass
$LHV = HHV - 2.44 * (8.94 * H2 + F)$			
LHV		**19,3**	**MJ/kg**

Table 3: conversion from HHV to LHV of values provided by [11]

In the same study, drawbacks of other forest residues are also mentioned: densification is required in the case of sawdust and shavings and impurities such as stones have to be removed from hogged wood and bark. Moreover, these residues generally have a high moisture content which makes them unsuitable fuels for a downdraft gasifier.

3.2.1.2 Other considerations about wood

However, supplying the quantity of wood required to run the gasifier is not always easy. It may be easy in developed countries covered with forests, such as Sweden: indeed, in such countries, forests are well-managed, efficiently utilized, and only few people rely on harvesting forests to meet their energy requirements. The competition for the use of forests is therefore not so strong, and is anyway controlled by efficient regulations and institutions. Moreover, infrastructure, such as roads, already exists and facilitates the organization of supply chains.

In developing countries, the situation is much different. In desert or semi-desert areas, wood resources are usually endangered because of their scarcity and the inefficient use that is made of them. In tropical areas, wood resources are more abundant, but the pressure on rainforests is high, and using the wood for gasification might worsen the deforestation issue. In any cases, the challenge is to find sustainable sources of wood supplies, which would not jeopardize the renewability index of the resource and the ability of local population to fulfill their energy needs.

3.2.2 Agricultural residues

3.2.2.1 Efficiency of the gasification of agricultural residues

The gasification of agricultural residues has been extensively investigated. In 1979, Williams & Goss [11] compared the yields obtained in a laboratory downdraft gasifier from different fuels, including walnut shells, rice hulls or cotton gin trash, with air as the gasification agent.

Various studies ([10], [12]–[14]) studied the suitability of various kind of biomass for gasification. Their main results are gathered in Table 4 below. The performance of the gasification ("yield" column in Table 4) is expressed in different ways. Williams & Goss [11] define it as

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[1] The yield is here defined as (Net heat of combustion of syngas)/(HHV of biomass fuel * fuel consumption rate)

$$Yield = \frac{Net\ heat\ of\ combustion\ of\ syngas}{HHV\ of\ biomass\ fuel\ *\ fuel\ consumption\ rate}$$

The other paper, when they measure the performance of the gasification, describe the quantity of gas produced in terms of m^3, or the electricity produced in kWh, as a function of the consumption of fuel.

While most of these residues have a raw HHV between 16-20 MJ/kg, their gasification do not result in the same yields and therefore their syngas have various HHV. In terms of gasification efficiency, walnut shells and rice husks seem to be the best fuels with respectively 6.2 and up to 6.5 MJ/m^3 of syngas.

Table 4: Fuels for gasification - literature review

Article	Year	Fuels	Pros	Cons	HHV biomass	HHV gas	Yields
Williams & Goss [11]	1979	Walnut shells	High HHV gas High yield	granular size consistency leading to issues with fixed bed	20,5 MJ/kg	6,2 MJ/m3	75,5 %
		Rice hulls		Low HHV gas requires pre-treatment low bulk density high ash content leading to high concentration of particules in gas	16,8 MJ/kg	3,4 MJ/m3	46 %
		Cotton gin trash		Low HHV gas requires pre-treatment handling issues	16,8 MJ/kg	4,5 MJ/m3	52 %
		Wood chips (residues)	High HHV gas Low ash content suitably sized material		20,5 MJ/kg	5,6 MJ/m3	60 %
		Corn cobs	High HHV gas Low ash content suitably sized material		19 MJ/kg	5,5 MJ/m3	55,5 %
van der Drift [10]	2001	Cacao shells			20,5 MJ/kg	4,61 MJ/m3	
Karmakar [12]	2013	Rice husks				3,53 - 6,50 MJ/m3	1,09 - 1,42 m3/kg
Mbohwa [13]	2003	Sugar bagasse	high power output	technology not yet available (biomass integrated steam turbines)			500 kWh/t cane
Deepchand [14]	2001	Sugar bagasse			19,3 MJ/kg (0% moisture)		
					10 MJ/kg (48% moisture)		
		sugarcane					150 kWh/t cane

3.2.2.2 Other aspects of the use of agricultural residues

3.2.2.2.1 Usage conflicts

Agricultural residues are already used by local population for other purposes. Buragohain *et al.* [15] mention several conventional uses for each type of residues. For example, cereal straws are often used for feeding cattle and sugarcane trash are burnt in fields. The authors also mention that several types of residue are already used as fuel, either for small factories or as domestic fuels. For example, sugarcane bagasse is often already used as fuel in sugar factories. Estimations of the fraction of residues available for power generation vary considerably, from 15-20% [15] to 30-100% [16]. The latter range is defined more precisely in [16] according to the origin of the residues; in particular, it has been evaluated around 30 to 40% for cereals residues.

3.2.2.2.2 Harvesting and pre-treatment issues

The use of agricultural residues in a gasifier raises several issues related to their storage and pre-treatment.

The first issue is temporal. In many regions in the world, harvesting of one type of crop takes place during a limited period of the year, lasting for a few weeks to a few months. As a consequence, to produce electricity all year long, the fuel must be stored. This requires large amounts of free space. In addition, if the fuel is stored in bad conditions, it might be exposed to humidity, which would make it more difficult to gasify and lower the gasifier's yields.

However, evidence can be found in the literature (e.g. [17]) that preliminary steps before gasification (harvesting, storage, drying, etc.) are already mastered and should not be blocking points.

4 Potential market for gasification units in developing countries

4.1 WISDOM-based methodology

This first approach is based only on wood resources.

4.1.1 What is WISDOM

In order to properly assess the available quantity of sustainable wood available in developing countries, we used the WISDOM studies (Wood fuel Integrated Supply / Demand Overview Mapping, [18]–[20]) published by the *Food and Agriculture Organization* (FAO) of the United Nations. WISDOM is a "spatially-explicit planning tool for highlighting and determining wood fuel priority areas"[18]. The studies that were used aim at identifying areas with deficit or abundance of wood fuel, based on the comparison of wood fuel supply and consumption patterns. They were conducted for East Africa [20] and South-East Asia [19].

The main interest of these studies is that they provide a picture at the national level from a local scale analysis. In [20] and [19], supply and demand data were compared within 9x9 km-cells (5 arc-minutes cells), which is roughly consistent with the distance that poor, rural population can cross to gather the wood fuel they require for their everyday uses. However, the accuracy of the data which was used came down to 0.9 x 0.9 km (30 arc-second) cells in some cases, but was aggregated because it "appeared far too fine for the purpose of the study and for achieving a meaningful supply/demand relation"[20].

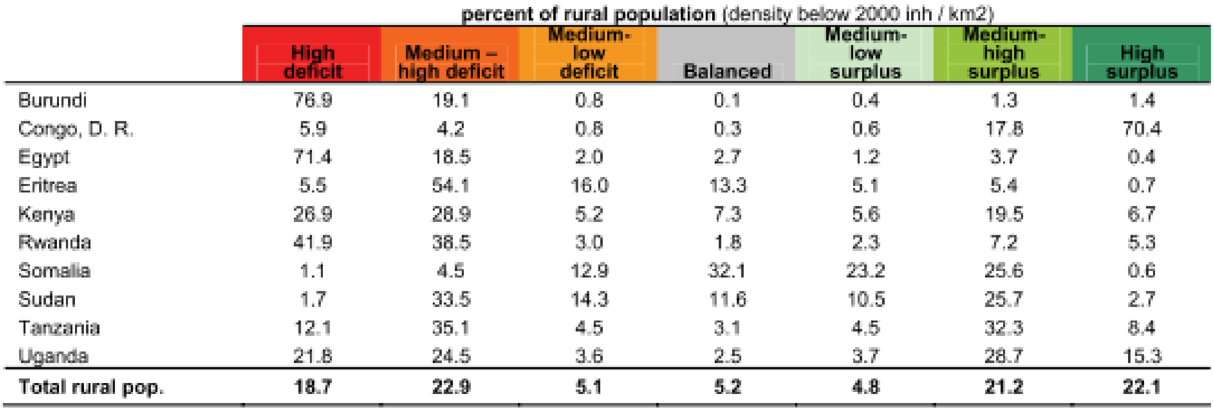
The input data for these WISDOM studies are mainly population distribution maps and woody biomass maps.

The population is classified among three categories: urban, sparse rural and rural settlements. The distinction between the 2 rural categories is made based on population density, with the threshold being 2000 inhabitants per square kilometer. This population data is then matched with national per capita consumption of wood in urban and rural areas, which allows calculating the wood fuel consumption in each cell according to the type and number of inhabitants living in it.

Woody biomass resources are estimated based on LCCS (Land Cover Classification System) maps edited by the FAO. Then, an annual sustainable production of wood is calculated by taking into consideration the density and the types of biomass that can be found in each cell.

Once the sustainable wood resources and the consumption of wood by the population have been assessed, the deficit or surplus of wood in each cell can be calculated. 'Surplus' here means that the consumption of wood by the population does not jeopardize the capacity of forests to regenerate every year. Said differently, there is a wood surplus in an area when the consumption of wood is lower than the annual production of biomass in the same area.

Further analysis of the results of these studies was made by Drigo [20] which allowed to determine the fraction of the rural population living under each balance category (7 categories ranging from High deficit to High surplus). An example is shown in Table 5. This kind of aggregated data is particularly valuable when trying to assess the potential market for power generation from gasification, as it provides information both on the population that could require electrification (the fraction of rural population without access to electricity can be found in statistics from international organizations) and on the ability of those population to have access to sustainable sources of wood, that can therefore be used in a gasifier.



	percent of rural population (density below 2000 inh / km2)						
	High deficit	Medium – high deficit	Medium-low deficit	Balanced	Medium-low surplus	Medium-high surplus	High surplus
Burundi	76.9	19.1	0.8	0.1	0.4	1.3	1.4
Congo, D. R.	5.9	4.2	0.8	0.3	0.6	17.8	70.4
Egypt	71.4	18.5	2.0	2.7	1.2	3.7	0.4
Eritrea	5.5	54.1	16.0	13.3	5.1	5.4	0.7
Kenya	26.9	28.9	5.2	7.3	5.6	19.5	6.7
Rwanda	41.9	38.5	3.0	1.8	2.3	7.2	5.3
Somalia	1.1	4.5	12.9	32.1	23.2	25.6	0.6
Sudan	1.7	33.5	14.3	11.6	10.5	25.7	2.7
Tanzania	12.1	35.1	4.5	3.1	4.5	32.3	8.4
Uganda	21.8	24.5	3.6	2.5	3.7	28.7	15.3
Total rural pop.	**18.7**	**22.9**	**5.1**	**5.2**	**4.8**	**21.2**	**22.1**

Table 5: Fraction of rural population living under each wood balance category (adapted from (Drigo, 2006))

4.1.2 Methodology

We used the WISDOM results to assess the potential market for gasifiers in the two sub-regions that this report chose to focus on, which are already covered by supra-national WISDOM studies: East Africa and South-East Asia.

We only looked at rural population, which is the client's target. Ideally, it would have been better not to consider too sparse rural settlements. Indeed, if the population density is too low, it means that a distribution network needs to be built, which considerably increases the capital cost of the project. Even though the population datasets used in the WISDOM studies differentiate between sparse rural population (< 2000 inh/km^2) and rural settlements (> 2000 inh/km^2), the aggregated results were only calculated for sparse population. Therefore, we used those figures for our calculations (see Table 5).

We took into consideration only areas that have at least a medium-high wood surplus, which corresponds to a surplus higher than 29.5 tons of wood per year per cell. Indeed, considering

- that the dimension of a cell is 30 arc-second * 30 arc-second, i.e. 0.73 km^2
- a population density of 2 000 inhabitants/km^2
- a conversion factor of 1 kWh of electricity produced from 1 kg of wood (figure provided by Xylowatt, which is supposed to represent the average performance of their technology),

we calculated that a minimum of 18.5 kWh per year per inhabitant could be produced in those areas. Using a lower threshold, like medium-low surplus, leads to a production below 3 kWh/year/inhabitant, which is rather low and would only cover basic domestic usage. According to paragraph 2.4.1, an appropriate ratio would be around 6-7 kWh of electricity per person per year, if some community services are also powered. The higher ratio of 18.5 kWh would correspond to a large village or small city with more economic activity.

Figure 4 shows the calculation steps of the WISDOM-based methodology.

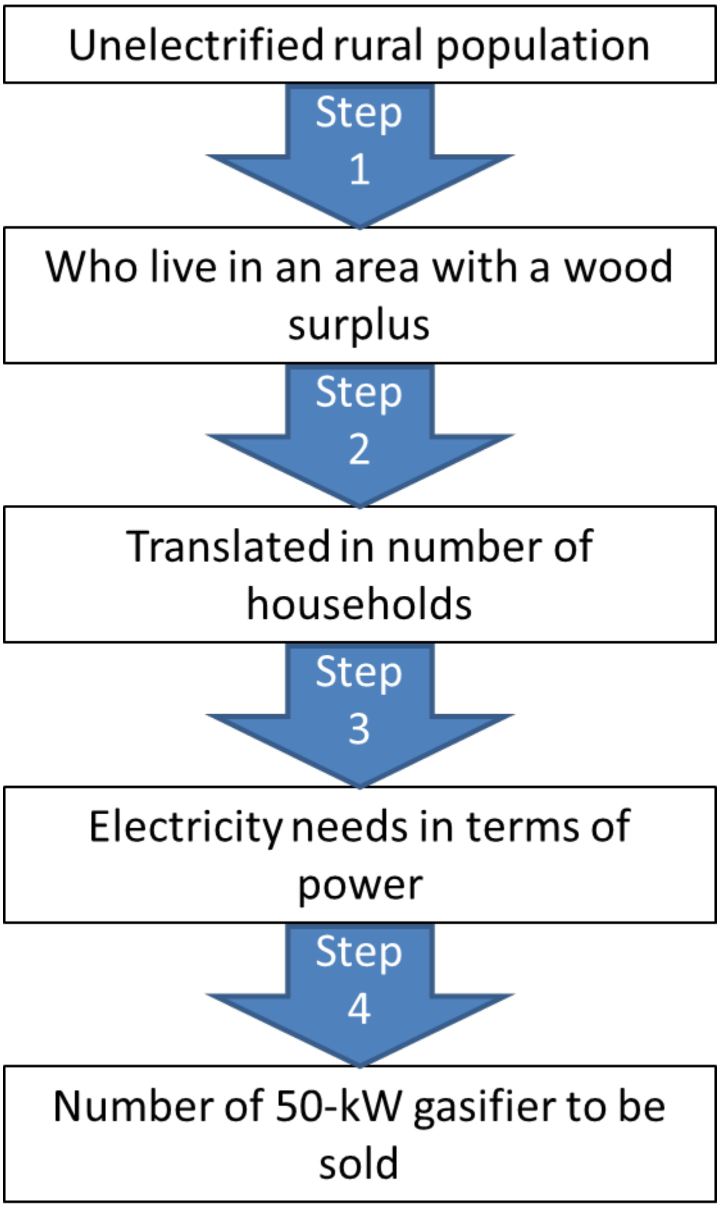


Figure 4: Calculation steps for the WISDOM-based methodology

Step 1

Statistics from the World Bank [21] gives the rural population who do not have access to electricity in most countries in the world. Using the aggregated values discussed above from the WISDOM studies, these unelectrified population figures were converted into rural population who have no access to electricity but who live in areas with a sufficient wood surplus.

Step 2

The population, expressed in number of persons, was converted in number of households using figures provided in [22]. For South-East Asia, figure from the Philippines was used. For East Africa, the mean value of figures from Mali, Kenya, South Africa and Senegal was used. These figures are provided hereafter in Table 6, together with values from countries which are not part of this study, for information.

Mali	10,0
South Africa	4,5
Morocco	6,0
India	7,5
Mexico	5,0
Brazil	5,5
Argentina	4,6
Kenya	6,0
The Philippines	5,2
Senegal	8,6
South-East Asia	5,2
East Africa	7,3

Table 6: Average size of households in selected countries [22]

Step 3

We considered that 1000 households required 150 kW of electricity, mainly based on co-workers experience feedbacks. This order of magnitude is consistent with [22], whose data is reproduced in Table 7 below.

Countries	Average domestic power capacity in Wp (peak watts)
South Africa	60
Argentina	400
Brazil	90
India	45
Kenya	18
Mali	50
Marocco	90
Mexico	100
The Philippines	80
Senegal	50
Average	**98,3**
Average excl. Argentina	**64,8**

Table 7: Average power capacity installed for domestic appliances, by household (from [22])

Step 4

This installed capacity was basically divided by 50 kW, which is the nominal power of our client's gasifier, in order to obtain the potential number of gasifiers that could be sold.

4.1.3 Results

	South-East Asia	East Africa
Unelectrified rural population	204 819 011	156 901 715
1		
Who live in an area with a wood surplus	9 606 698	71 973 939
2		
Translated in number of households	1 847 442	9 893 325
3		
Electricity needs in terms of power	277 116 kW	1 483 999 kW
4		
Number of 50-kW gasifier to be sold	**5542**	**29 680**

This methodology based on the equilibrium between the available wood resources and their usage gives surprising results. Even though South-East Asia and East Africa present similar rural population without electricity, and South-East Asia is a rather woody subregion, it appears that East Africa has a significantly higher potential. This is mostly due to the fact than in South-East Asia, the areas with wood surplus are not inhabited by enough population requiring electrification.

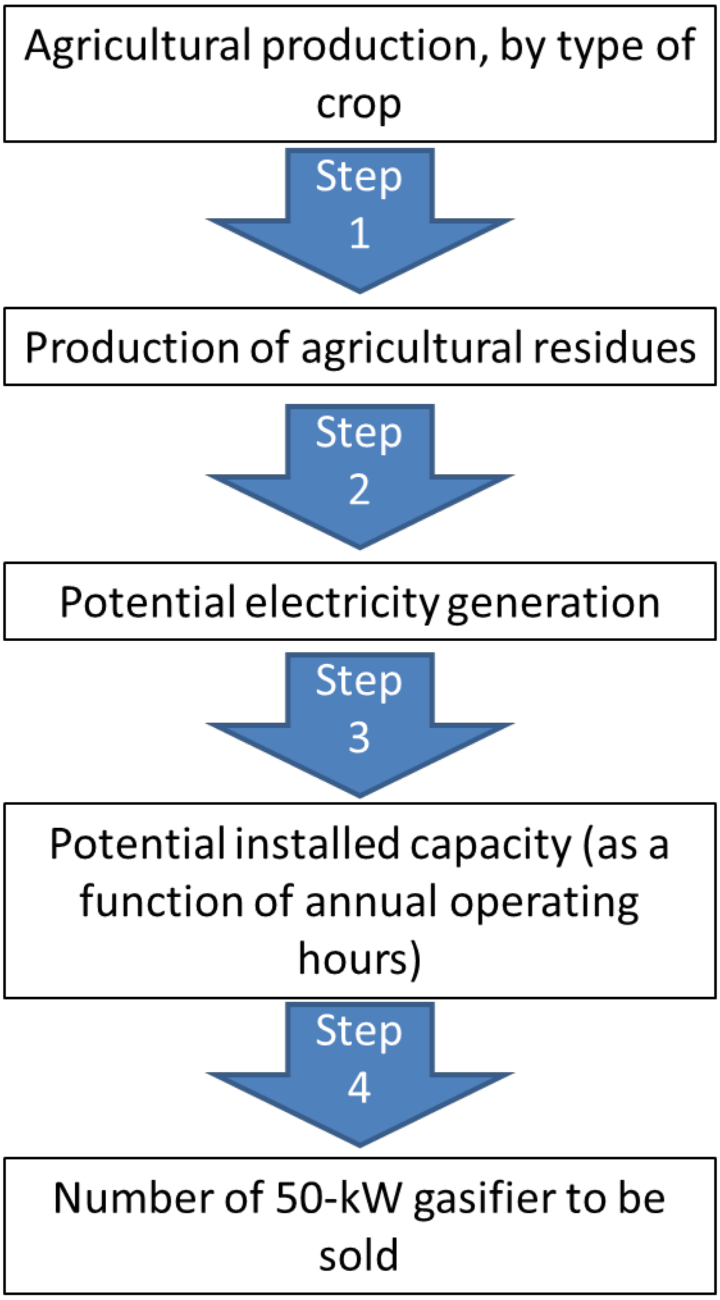
4.1.4 Limits and ways of improvement of the methodology

The main limit is of course that WISDOM studies are only available for a limited number of countries for the moment. However, other WISDOM studies have been carried out at national and sub-national levels and might be used for more local market studies. We did not use them as the initial purpose of the study was to get a worldwide picture.

Another limit is that these studies only consider woody resources, which represent only a fraction of the available biomass. In following paragraphs, other sources of biomass are discussed.

4.2 Methodology based on agricultural residues

4.2.1 Methodology description



Step 1

The first step consisted of determining the agricultural production in every country. This has been done using datasets published by the FAO in the FAOSTAT databases [23]. Data about the production of cereals and nuts were extracted, by country and type of crop, for the year 2011 (most recent year in the database at the time of the study).

Country	Item	Element	Year	Unit	Value	Flag
Algeria	Almonds, with shell	Production	2010	tonnes	44 300	FAO estimate
Algeria	Barley	Production	2010	tonnes	1 500 000	Unofficial figure
Algeria	Cotton lint	Production	2010	tonnes	20	FAO estimate
Algeria	Cottonseed	Production	2010	tonnes	28	FAO estimate
Algeria	Groundnuts, with shell	Production	2010	tonnes	3 600	FAO estimate
Algeria	Maize	Production	2010	tonnes	510	FAO estimate
Algeria	Oats	Production	2010	tonnes	85 400	FAO estimate
Algeria	Olives	Production	2010	tonnes	555 200	FAO estimate
Algeria	Potatoes	Production	2010	tonnes	3 290 000	Unofficial figure
Algeria	Rapeseed	Production	2010	tonnes	42 900	FAO estimate
Algeria	Rice, paddy	Production	2010	tonnes	220	FAO estimate
Algeria	Seed cotton	Production	2010	tonnes	62	FAO estimate
Algeria	Sorghum	Production	2010	tonnes	350	FAO estimate
Algeria	Sunflower seed	Production	2010	tonnes	50	FAO estimate
Algeria	Triticale	Production	2010	tonnes	0	FAO estimate
Algeria	Wheat	Production	2010	tonnes	3 100 000	Unofficial figure

Figure 5: Example of the FAOSTAT website output for Algeria [23]

These figures were then converted into agricultural wastes using crop-to-residue ratios (CRR), which describe the quantity of residues produced either per harvested area (e.g. [24]) or per mass of crop production (e.g. [15], [24]). The crop-to-residues ratios (in tons of residues produced per tons of crop harvested) that we used are given in Table 8.

Crop residue	CRR	Source
Rice husks	0.3	[15]
Sugarcane bagasse	0.3	[14], [15], [25]
	0.278	[26]
Wheat	1.1	[27]
Maize	2.0	[27]
Soybeans	1.7	[27]
Cassava	0	Subsistence farming: dispersed resource not suitable for gasification

Table 8: Crop-to-residue ratios used in this study

According to [15], only about 15% of the crop residues are not already used for other purposes than energy use. Of course, this ratio depends on the type of residues. However, specific usage values for each type of residue are hard to determine, therefore this 15% ratio has been applied to all types of residues.

Step 2

As seen in the section 3.2.2.1, the HHV of the producer gas varies depending on the kind of residues that are gasified. However, in order to simplify the calculation, we considered that 2 kg of residues were required to produce 1 kWh of electricity, whatever the kind of residue and disregarding the specific details of the conversion technology. This ratio was provided by our client.

Step 3

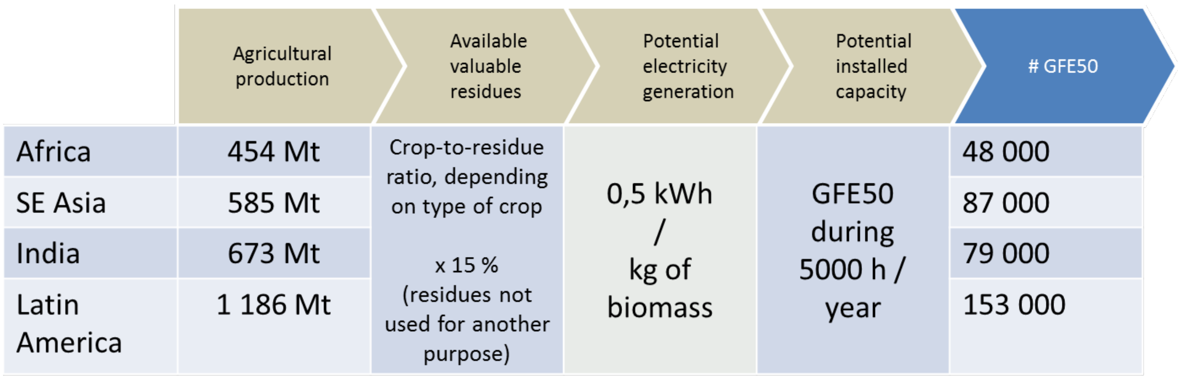
To convert this amount of electrical energy into power capacity, we had to make assumptions on the yearly operating hours of the gasifiers. Such an assumption would be more relevant in the frame of a specific techno-economic analysis, where the needs of the final users are known. In order to take into account the wide variety of situations that can occur, we made calculations for two cases: gasifiers operating 2000 hours per year, and 5000 hours per year.

Step 4

The final step simply consists in dividing the total potential installed capacity by the power of one gasifier, which is 50 kW_e.

4.2.2 Results

The potential number of gasifiers that could be installed was calculated in three global regions: South-East Asia (excluding India), Africa and South America, and in India separately. A summary of the results can be found in Table 9 and Figure 6, while more detailed data is given in Appendix 1.



	Agricultural production	Available valuable residues	Potential electricity generation	Potential installed capacity	# GFE50
Africa	454 Mt	Crop-to-residue ratio, depending on type of crop x 15 % (residues not used for another purpose)	0,5 kWh / kg of biomass	GFE50 during 5000 h / year	48 000
SE Asia	585 Mt				87 000
India	673 Mt				79 000
Latin America	1 186 Mt				153 000

Table 9: Estimated market based on agricultural residues

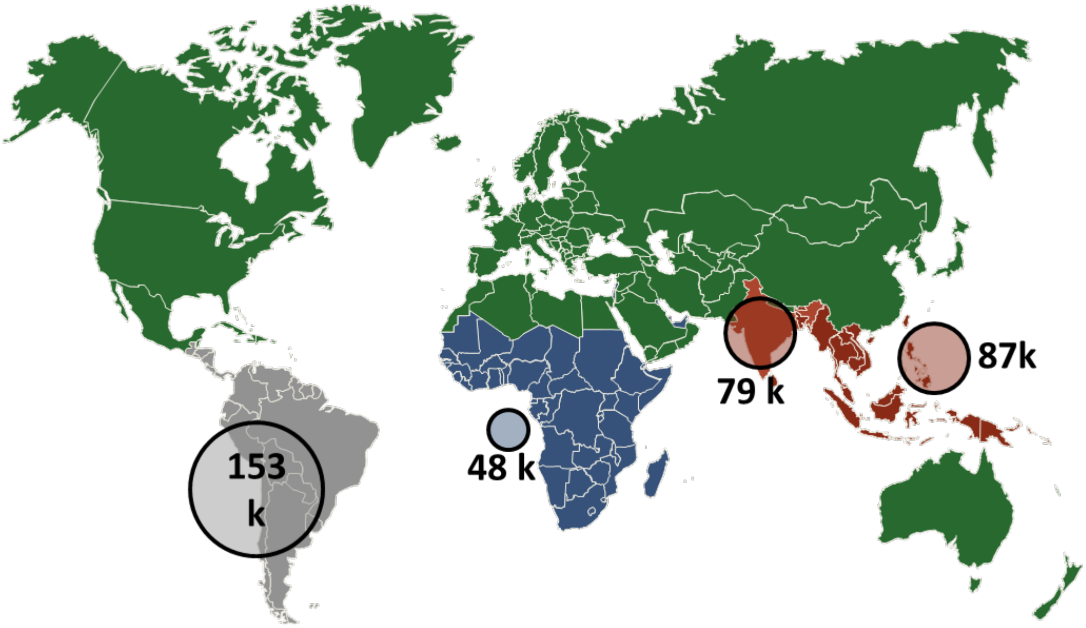


Figure 6: Map of the estimated market based on agricultural residues

Africa is penalized by its lack of agricultural resources. Without sufficient agriculture, there is obviously not enough agricultural residues available for gasification.

South America on the other hand has a significant amount of agricultural residues that could be used in gasifiers.

In South-East Asia, it can be noticed that India has almost as much residues as the rest of the region. Counted together, this is the region with the biggest amount of agricultural residues, and therefore a very relevant area to study more in depth.

4.2.3 Limits of the methodology

This methodology does not take into account the population that needs electrification. For example, in South America, large quantities of crops are cultivated and therefore produce lots of residues that could be converted into electricity, but most of the population in those intensive agricultural regions has already access to electricity and might not need new power capacity.

4.3 Methodology based on unelectrified population

4.3.1 Methodology description

In this estimation, only demographic data and assumptions were used. It is therefore based on the needs for electrification instead of available resources.

This methodology relies on data from the World Bank, quantifying the population without access to electricity in every country in the world. Then, several filters are applied to take into account the typical size of households, their electricity needs and the proportion of large villages. These choices are explained step by step in the following paragraphs.

An overview of the different steps is given in Figure 7.

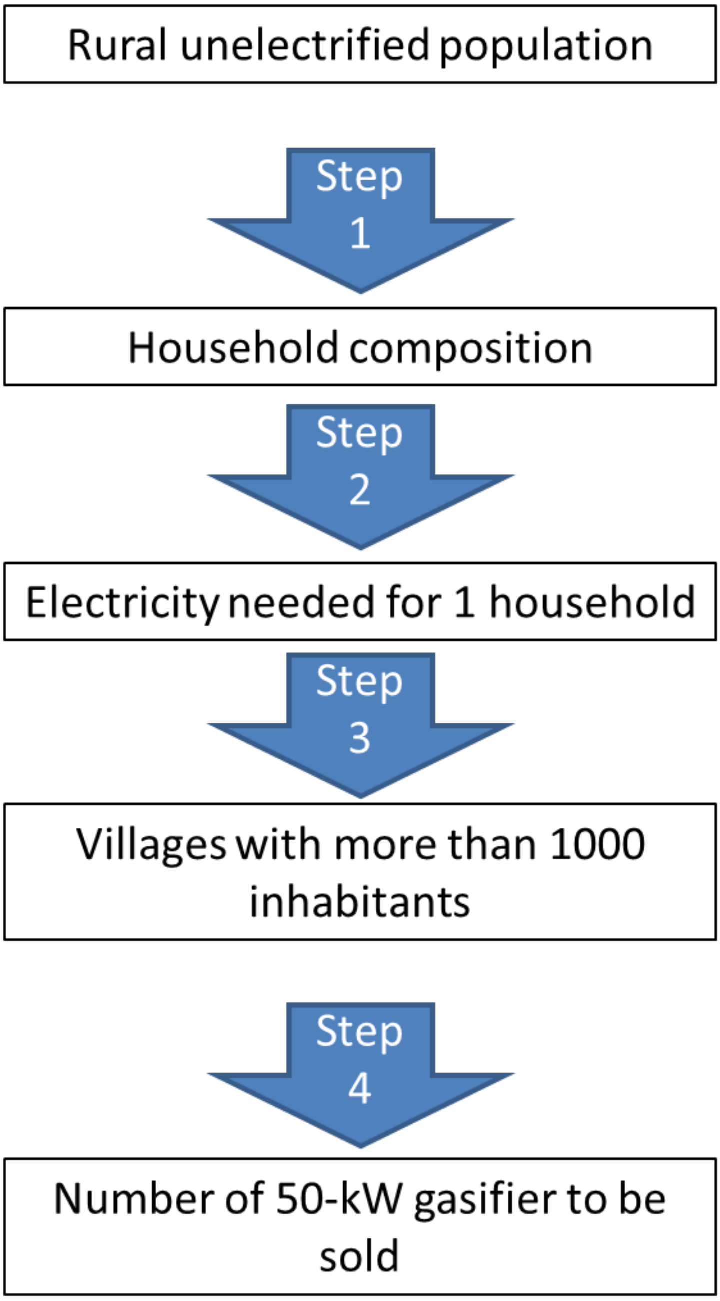


Figure 7: Chart of the methodology based on unelectrified population

Step 1

The statistics from the World Bank give the number of persons who do not have access to electricity. However, in most studies, the unit used to quantify the population is one household. Indeed, electric equipment is generally shared inside a household.

Sizes of families for various countries are given in [22] and are summarized in Table 6. These values were averaged and extrapolated to the regions under study, and the following values were used in our calculations:

Region	**Household size**
Africa	7
South Eastern Asia	6,4
South America	5
India	7,5

Table 10: Household sizes used in this study

Step 2

Reference [22] gives also the average electric capacity in the ten countries that they studied. These figures are reproduced in Table 11.

Country	**Domestic electricity capacity installed**, in Wp
South Africa	60
Argentina	400
Brazil	90
India	45
Kenya	18
Mali	50
Marocco	90
Mexico	100
The Philippines	80
Senegal	50
Average	**98,3**

Table 11: installed capacity for rural households in some countries (from [22])

In our calculation, we considered an installed capacity of 150 W per household, in order to take into account the fact that having access to a stable electricity supply, the users would inevitably increase their demand.

Step 3

Villages that are too small would require a connection to a grid, as they would not use all the electricity produced by one gasifier. To get an approximation of the share of villages that are large enough in each sub-region, we used a statistic from [9] stating that in Senegal, 5% of the villages had more than 1000 inhabitants. Then, statistics from the World Bank provides the rural population and the land area, which allows calculating a rural population density. Finally, the 5% from Senegal are extrapolated to the rest of the world as detailed in Table 12.

Sub-Region (World Bank's denomination)	Rural population (million)	Land area (1000 sq. km)	Rural density (inhab./ sq.km)	Extrapolated percentage of villages > 1000 inhabitants
East Asia & Pacific (developing only)	1028	15853	65	**13%**
Latin America & Caribbean (developing only)	123	20115	6	**1.3%**
Sub-Saharan Africa (developing only)	545	23588	23	**5%**

Table 12: estimation of the share of village with more than 1000 inhabitants

4.3.2 Results

The methodology has been used to study the same areas that were already considered in § 4.2 in order to allow comparisons. The results are presented in Table 13 and Figure 8 below.

	Rural unelectrified population	Household composition	Household's electricity need	Villages > 1000 inhabitants	# GFE50
Africa	479 M	7	150 W / household	5 %	10 000
SE Asia	177 M	6,4		13 %	11 000
India	358 M	7,5		13 %	19 000
Latin America	18,8 M	5		1,3 %	140

Table 13: Estimated market based on unelectrified population

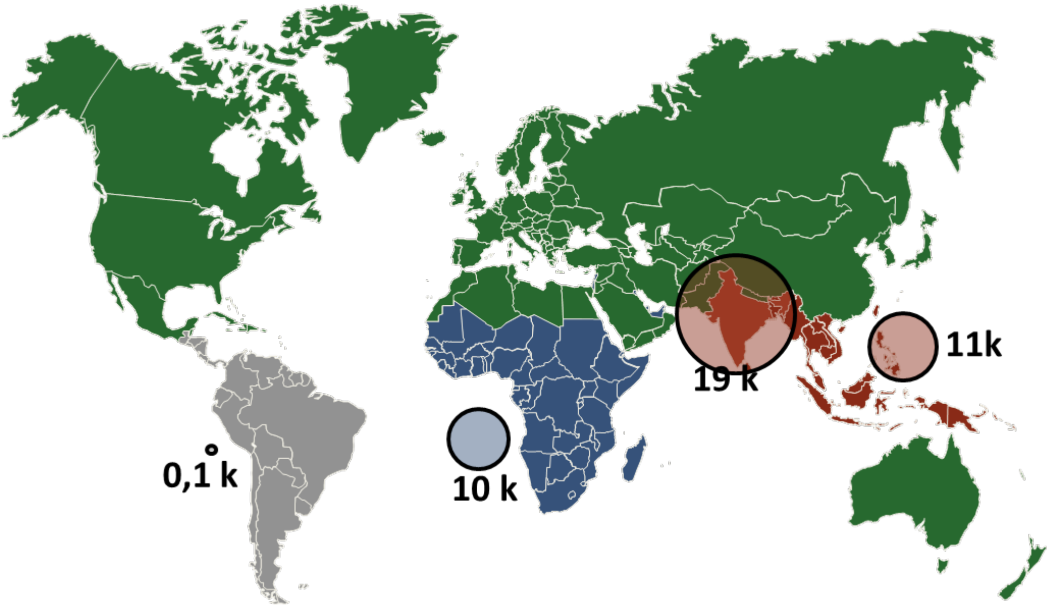


Figure 8: Map of the estimated market based on unelectrified population

Apart from the order of magnitude, the main difference with the results from § 4.2.2 can be seen in South America. With this methodology, the market in this region is almost non-existent. This is due to the already high level of access to electricity and the quite low rural density.

In Africa, despite low electrification rates, the market does not appear so big. It is limited by the rather sparse rural living conditions.

Interestingly, India and South-East Asia present the highest potential: there are still quite a lot of people requiring access to electricity in these regions.

4.3.3 Limits of the methodology

The main limit of this methodology is the determination of the rural population density. As an example, Figure 9 shows the potential market if the "villages > 1000 inhabitants" limitation is not taken into account. In this case, Africa would be a very large market.

In other words, one factor which is quite difficult to evaluate leads to significant variations in the final result.

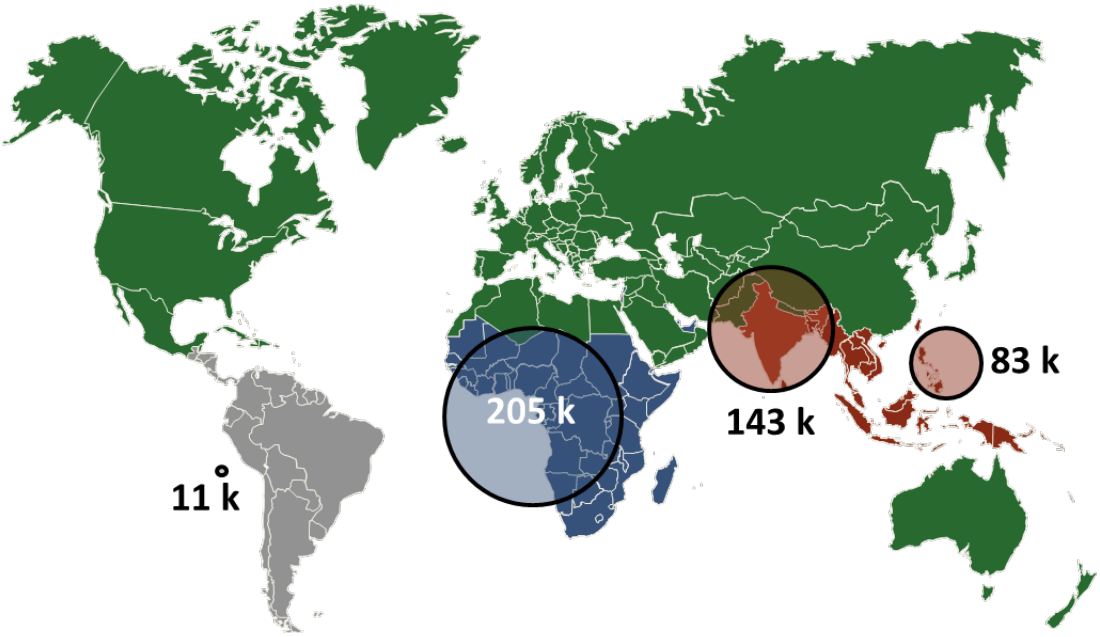


Figure 9: Map of the estimated market based on unelectrified population, without taking into consideration the population density represented by the average village size.

4.4 Determining priority countries for further investigation

4.4.1 Purpose

One of the objectives of the study was to identify a few countries which would be most interesting to investigate more deeply in terms of market potential. The ideal country is a country where there is a lot of biomass suitable for gasification, as well as a strong need for electrification. As those two points were studied separately in 4.2 and 4.3, it is only necessary to find a way of comparing the figures provided by these two methodologies. To do so, a score-based methodology has been used.

4.4.2 Methodology

Two criteria have been compared: the mass of agricultural residues produced in the country and the unelectrified population. These two criteria are a little bit less accurate than the figures calculated with the methodologies presented in 4.2 and 4.3. The agriculture criterion does not take into account the crop-to-residue ratio; the unelectrified population criterion does not take into consideration the size of villages. However, the purpose of this calculation was to have a quick assessment of the countries that should be investigated more deeply, and a rough comparison of the volume of the market in each country was deemed to be enough at that time.

The scores have been calculated using a simple methodology: all countries were first ranked according to their production of agricultural residues (respectively unelectrified population) in absolute value, and then a score of 20 has been attributed to the country with the biggest production of agricultural residues (resp. unelectrified population). Then, every other country has been granted a score between 0 and 20, proportionally to the country with the highest score.

In reality, some adjustment had to be made: some countries have an agricultural production (e.g. Brazil) or an unelectrified population (e.g. India) so much higher than all the other countries that they were given score over 20. Otherwise, most of the countries would have scores so low that it would not be convenient to use them.

At this point, each country is defined by two scores. In order to have only one score for each country, the minimum value from those two has been taken. Indeed, if one of the two scores is low, it means that there is a limiting factor in the country (either no resource to be gasified or no population that needs electrification).

4.4.3 Results

The results of this calculation have been translated into a world map, shown in Figure 10. Countries in green and yellow have most potential, according to the simple methodology explained in §4.4.2.

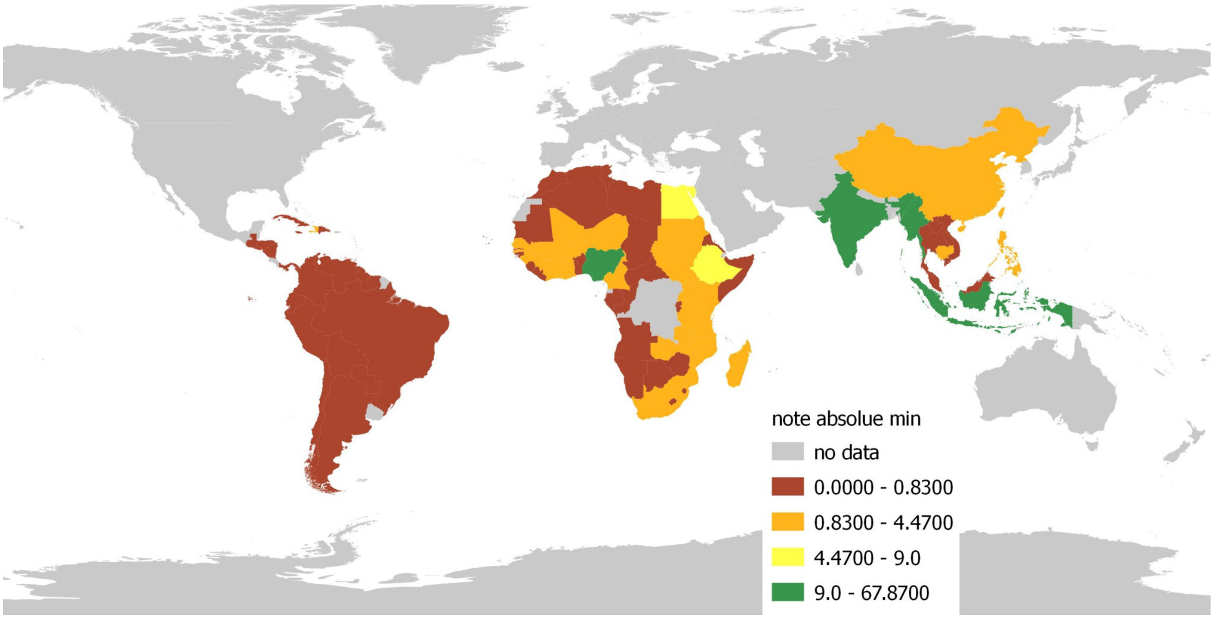


Figure 10: Preliminary selection of countries for further investigation

South-East Asia appears to be a promising area, with India, Myanmar and Indonesia hitting top scores. In Africa, Nigeria gets a good score too. Egypt and Ethiopia have less potential, but might still be considered in a second step.

Latin and South America gets a low score because of its already high rate of electrification. In addition, agriculture in this area is mostly based on large farms or ranches, therefore the power capacity of the proposed gasifier is too small and may not be applicable there.

Other African countries than those already mentioned are penalized by their lack of agricultural resources.

The map in Figure 11 shows, for each country, which is the limiting factor : lack of agricultural residues (in green) or lack of population requiring electrification (in blue).

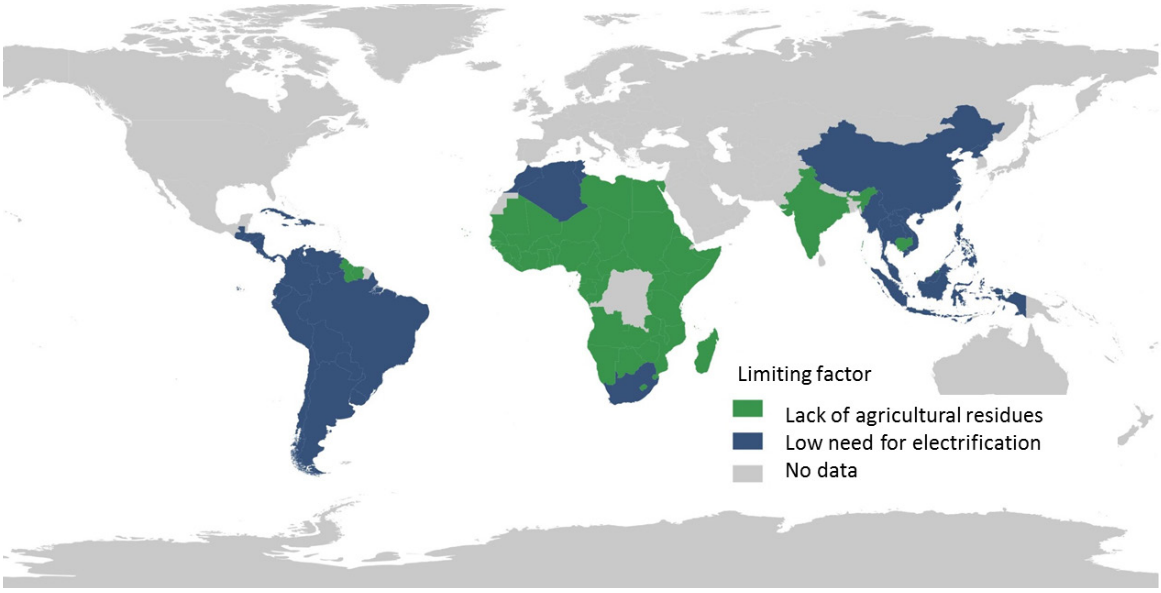


Figure 11: Map of limiting factors for each country

Of course, in countries where there are large amount of agricultural residues and, at the same time, a high need for electrification, none of the factor is really limiting. Therefore, this map must be read together with the map on Figure 10.

4.4.4 Limits of the methodology

This methodology relies on basic data and simplified calculations. It only gives a general idea of the most promising countries. Whereas countries with a high score are likely to be definitely promising, countries with a low score might still be interesting thanks to some local specificities, such as particular industrial or agricultural sectors, or favorable politics, infrastructure etc. Some more detailed ways of investigation are developed in the following paragraphs.

4.5 Methodology based on the study of some industrial or agricultural sectors

4.5.1 Description of the methodology

One of the commercial targets of our client was the small and medium industries which produce residues that can be gasified. The most obvious is the sugar industry, where extensive research has been carried out about the potential for energy production from sugarcane bagasse, often by using cogeneration, for example in Brazil [7],in India [28], in Zimbabwe [13], [25] or in Mauritius [14]. Many of these papers present gasification as a technological route for the production of electricity from bagasse which could lead to improved efficiency but still requires technological development and cost optimization.

The most interesting sectors to investigate are those which involve an energy-intensive process, like drying or coffee roasting, and produce residues that are suitable for gasification. In addition to the sugar industry, the following were investigated: tea factories, coffee factories, rice mills, saw mills.

We first intended to find industries that could use a 50- or 200-kW gasifier to satisfy their own energy needs. Therefore, the first step has been to understand the energy consumption associated with the different processes (e.g. kWh required to mill 1 ton of rice or to dry 1 ton of sugar cane). Results are gathered in Table 14. This allows getting an idea of the size of the plants (in terms of production capacity) that can be targeted by our client (see Table 15).

The final step consisted of finding the number of plants that have the right size. This was done thanks to a market research focusing on some particular industries in selected countries, as described in Table 16. The selection of countries is mainly based on the available data that can be found, which should be, to some extent, representative of the market size, dynamism and accessibility. However, there is also a part of arbitrary choice, enhanced with the knowledge of senior consultants. For agricultural sectors, the countries that were studied are all located in South-East Asia (& India). For the wood industry, Central Africa has more arguments.

Type of industry	Electricity consumption	Thermal energy consumption
Rice mill	20 kWh / ton of rice	81 kWh / ton of rice
Sugar factory	20-30 kWh / ton of sugar	n/a
Tea factory	400 – 700 kWh / ton of tea	4.5 – 6.8 MWh / ton of tea
Sawmill (wood)	15 kWh / m^3 for sawtimber 150 – 230 kWh / m^3 for plywood	

Table 14: Energy consumption of some rural industry of interest for gasification

Type of industry	Target capacity for a GFE50	Target capacity for a GFE200
Rice mill	2.5 tons of rice / hour	10 tons of rice / hour
Sugar factory	15-25 tons of suger / day	60-100 tons of sugar / day[1] [2]
Tea factory	450 tons of tea / year [3]	1800 tons of tea / year [3]
Saw mill	Saw timber: 16 500 m^3 / year Plywood: 1075 m^3/year	Saw timber: 66 000 m^3 / year Plywood: 4300 m^3/year

Table 15: Typical capacity of plants to be targeted

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[2] assuming 10 operating hours per day

[3] assuming 5000 operating hours per year

Type of industry	Selected countries for a market research
Rice mill	Cambodia India The Philippines
Sugar factory	Thailand The Philippines India Indonesia
Tea factory	India Sri Lanka
Saw mill	Cameroon Ethiopia Nigeria Kenya Indonesia

Table 16: Countries selected for deeper market research, for some industrial sectors

4.5.2 Results

4.5.2.1 Rice industry

In **Cambodia** [29], out of 90 identified gasification projects, a half take place in rice mills, and concern gasifier with a capacity of 200 kWe. This shows that the sector is quite interested by the technology. However, there are only around 400 commercial rice mills (meaning with production capacity over 1 ton per hour), which means that there might not be so many mills that still need gasifiers.

In **India,** the average capacity of rice mills is 40 to 50 tons per day. Therefore, 50-kWe gasifiers seem more suitable. In Bihar, the company Husk Power Systems already installed 84 gasifiers, mostly with a nominal power capacity of 32-kWe each [30], [31]. In Karnal district, out of 221 mills, 85 % of the mills have a capacity of 1-2 ton per hour [32], which is below the size that makes a 50-KWe gasifier profitable with only self-consumption of the produced electricity.

In **the Philippines**, it is estimated that 1500 GWh of electricity per year can be produced from rice hulls and straws [33]. This would be equivalent to 1500 units of 200-kWe gasifiers running 5000 hours per year. However, this is a simplistic approach not taking into account the size of rice mills.

4.5.2.2 Sugar industry

In **Thailand**, there are 47 sugar factories, all with capacities ranging from 300 to 4000 tons of sugar per day [34] .

In **the Philippines**, there are 29 sugar factories with capacities over 200 tons per day [35].

In **India,** more specifically in Uttar Pradesh which is the main region producing sugar, there are 111 sugar factories with an average capacity of 54 000 tons of sugar per year, therefore a daily capacity over 150 tons [36].

In **Indonesia**, there are 75 sugar factories, with capacities ranging from 100 to 1200 tons a day [37].

As seen in Table 15, all these sugar factories are large enough to benefit from a 200-kWe gasifier, and even sometimes from several units. However, a strong competition with CHP must be expected. For example, in India, 211 out of 527 sugar factories are already equipped with CHP plants, with power capacities of several MW per factory [38]. Therefore, the gasifiers might even be too small.

4.5.2.3 Tea industry

In **India,** there are 1300 tea factories, with an average capacity of 700 tons per year. Such an average tea factory uses each year the energy produced by a 200-kWe gasifier running during 2000 hours a year, or a 50-kWe gasifier running 7700 hours a year (which is less realistic). The biggest factories with capacities over 1000 tons per year may be interested by a 200-kWe unit, while factories with capacities around 500 tons per year would prefer 50-kWe units. However, we do not have more information about the number of large and small factories.

In **Sri Lanka**, there are 800 tea factories, with an average capacity of 375 tons per year. 50-kWe gasifiers seem more suitable for this market made of smaller factories than the Indian ones.

As can be seen in §4.5.1, the production of tea requires 10 times more thermal energy than electricity. Cogeneration systems may therefore be investigated prior to gasifiers producing mainly electricity, which was the aim of Xylowatt.

Besides, no literature related to the gasification of tea leaves could be found and no actual tests could be performed by our client. Major operational issues might arise if using tea leaves in a gasifier designed for other types of biomass feedstocks.

4.5.2.4 Wood industry

Wood residues are an excellent fuel for gasification; therefore the wood industry must be investigated carefully.

The consumption of electricity in a wood factory varies by a factor of 10 depending on the type of output: the production of plywood is more energy-intensive than the production of saw timber. This makes it more complicated to assess the energy consumption of wood factories. Moreover, the countries which were investigated are mostly located in Africa, where statistics are not easily obtained. Some figures can be found anyway.

In **Cameroon** [39], which is the largest wood producer in Central Africa, there are 77 industrial sawmills. 15 of them produce over 66 000 m^3 per year and could be suitable for the 200-kWe gasifier. Around 30 sawmills have a production capacity between 15 000 and 60 000 m^3 per year, suitable for a 50-kWe gasifier.

In **Ethiopia**, sawmills are rather small, with capacities around 2500 to 3500 m^3 of saw timber per year. Most of them are below the size threshold of the 50-kWe gasifier.

In **Nigeria** [40], 1350 sawmills were registered in 1998, among which 6% are categorized as "large", without any further detail on what this means. As an estimation, less than 100 sawmills would be suitable for the installation of a gasifier.

In **Kenya** [41]**,** there are 73 "medium" or "large" sawmills. All of them produce enough wood residues to fuel a 50-kWe gasifier during 5000 hours a year, and 25% of them enough to fuel a 200-kWe gasifier during 5000 hours a year. However, none of them is large enough to consume the electricity produced.

In **Indonesia** [42], in 1991, there were 113 plywood factories with an average output of 60 000 m^3 per year. This means that each plant could use the electricity produced by several 200-kWe gasifiers.

4.5.3 Limits of this methodology

In this study, we calculated the minimal capacity that a plant should have in order to need the power from one gasifier. We found out that there are not so many agricultural plants (rice mills, sugar factories…) that are big enough to need 50 or 200 kW of electricity, which drastically reduced the market potential. Moreover, it means that all residues are not used as fuel.

Quick "table corner" calculation

~ 2,5 kg of rice husks produce 1 kWh, and 0,25 kg of husks is produced for 1kg of rice. Rice production needs 20 kWh_{el} per ton of rice.

Therefore, with the residues from the production of 100 tons of rice, enough electricity can be generated to produce 500 tons of rice.

However, one possibility for the owner of a gasifier is to sell the surplus electricity to surrounding consumers, who can be other industries or people. This is what most publications about the potential for power generation from sugar bagasse rely on (e.g. [13], [14]). The main barrier to this kind of projects is that it is only feasible if there are potential customers nearby, or if the factory is connected to an electric grid.

5 Conclusion

This report is built in 3 consecutive parts. First, an insight of the challenges to the access to electricity in rural areas in developing countries is given. Then, a short description of the gasification technology and its applications is provided, including the comparison of different types of feedstock that can typically be used in the targeted areas. Finally, the potential market for gasifiers in some representative areas of the developing world is assessed by analyzing all governing factors together, such as feedstock availability, need for electricity, population density, ability to pay for the service provided and ability to serve and maintain the hardware.

The achieved results represent a rough round-up of possible marketing opportunities by identifying and quantifying the most promising regions for technology deployment. Several methodologies were examined, which must be improved in order to assess more accurately the potential market for small-scale gasifiers in rural areas of developing countries. Using aggregated statistics and literature, several countries were identified as most promising, situated mostly in South-East Asia.

Apart from the limits inherent to the methodologies and the limited data on the gasifier performance, which impeded the possible scale and depth of the analysis, several additional key factors could not be assessed in this report and are instead recommended for complementing studies. This work needs to be expanded with additional examination on the profitability of the projects, careful economy analysis taking into account also some plausible governmental support schemes or international charity funds, the actual performance and maturity of the technology, and some detailed social factors that are specific to each regional market that can accelerate or hinder the development and deployment of biomass gasification and of other distributed power production technologies.

Bibliography

[1] "Gasification Technology | Gasification Process | The Notar Gasifier." [Online]. Available: http://www.xylowatt.com/index.php/solutions/the-notar-gasifier.html. [Accessed: 22-Feb-2014].

[2] H. Chum, A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. G. Eng, W. Lucht, M. Mapako, O. M. Cerutti, T. McIntyre, T. Minowa, and K. Pingoud, "Bioenergy," in *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)],*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2011.

[3] "IEA - Global status of modern energy access." [Online]. Available: http://www.worldenergyoutlook.org/resources/energydevelopment/globalstatusofmodernenergyaccess/. [Accessed: 11-Jun-2013].

[4] IRENA, "Prospect for the African Power Sector," 2011.

[5] "IEA - Energy Poverty & Health (WHO Collaboration)." [Online]. Available: http://www.worldenergyoutlook.org/resources/energydevelopment/energypovertyhealthwhocollaboration/. [Accessed: 12-Jun-2013].

[6] V. Modi, S. McDade, D. Lallement, and J. Saghir, "Energy services for the Millennium Development Goals," UNDP; World Bank; ESMAP, New York, 2006.

[7] G. A. Dantas, L. F. L. Legey, and A. Mazzone, "Energy from sugarcane bagasse in Brazil: An assessment of the productivity and cost of different technological routes," *Renew. Sustain. Energy Rev.*, vol. 21, pp. 356–364, May 2013.

[8] "Biomass Gasifier Manufacturers in India," *India Solar, Wind, Biomass, Biofuels - EAI.* [Online]. Available: http://www.eai.in/lists/top-companies/bio/biomass-gasifier-manufacturers-in-india. [Accessed: 04-Mar-2014].

[9] Z. Contreras, "Modèle d'électrification rurale pour localités de moins de 500 habitants au Sénégal," Deutsche Gesellschaft für Technische Zusammenarbeit, 2006.

[10] A. van der Drift, J. van Doorn, and J. . Vermeulen, "Ten residual biomass fuels for circulating fluidized-bed gasification," *Biomass Bioenergy*, vol. 20, no. 1, pp. 45–56, Jan. 2001.

[11] R. O. Williams and J. R. Goss, "An assessment of the gasification characteristics of some agricultural and forest industry residues using a laboratory gasifier," *Resour. Recovery Conserv.*, vol. 3, no. 4, pp. 317–329, Mar. 1979.

[12] M. K. Karmakar, J. Mandal, S. Haldar, and P. K. Chatterjee, "Investigation of fuel gas generation in a pilot scale fluidized bed autothermal gasifier using rice husk," *Fuel*.

[13] C. Mbohwa and S. Fukuda, "Electricity from bagasse in Zimbabwe," *Biomass Bioenergy*, vol. 25, no. 2, pp. 197–207, Aug. 2003.

[14] K. Deepchand, "Commercial scale cogeneration of bagasse energy in Mauritius," *Energy Sustain. Dev.*, vol. 5, no. 1, pp. 15–22, Mar. 2001.

[15] B. Buragohain, P. Mahanta, and V. S. Moholkar, "Biomass gasification for decentralized power generation: The Indian perspective," *Renew. Sustain. Energy Rev.*, vol. 14, no. 1, pp. 73–92, Jan. 2010.

[16] S. Cornelissen, M. Koper, and Y. Y. Deng, "The role of bioenergy in a fully sustainable global energy system," *Biomass Bioenergy*, vol. 41, pp. 21–33, Jun. 2012.

[17] A. V. Bridgwater, "The technical and economic feasibility of biomass gasification for power generation," *Fuel*, vol. 74, no. 5, pp. 631–653, May 1995.

[18] FAO, "WIDSOM - Woodfuels Integrated Supply / Demand Overview Mapping," 2003. [Online]. Available: http://www.fao.org/docrep/005/Y4719E/y4719e00.htm#TopOfPage. [Accessed: 09-Jun-2013].

[19] R. Drigo, "Wood-energy supply/demand scenarios in the context of poverty mapping. A WISDOM case study in Southeast Asia for the years 2000 and 2015," *Environ. Nat. Resour.*, vol. 27, no. 1, 2007.

[20] R. Drigo, "WISDOM – East Africa." FAO, 2005.

[21] "Data | The World Bank." [Online]. Available: http://data.worldbank.org/. [Accessed: 06-Jul-2013].

[22] Observ'er, "La production d'électricité d'origine renouvelable dans le monde, 4 - Actualisation de l'ERD dans dix pays.," EDF, 2008.

[23] "FAOSTAT." [Online]. Available: http://faostat3.fao.org/home/index.html. [Accessed: 10-Jun-2013].

[24] R. Lal, "World crop residues production and implications of its use as a biofuel," *Environ. Int.*, vol. 31, no. 4, pp. 575–584, May 2005.

[25] C. Mbohwa, "Bagasse energy cogeneration potential in the Zimbabwean sugar industry," *Renew. Energy*, vol. 28, no. 2, pp. 191–204, Feb. 2003.

[26] L. Mashoko, C. Mbohwa, and V. M. Thomas, "Life cycle inventory of electricity cogeneration from bagasse in the South African sugar industry," *J. Clean. Prod.*, vol. 39, pp. 42–49, Jan. 2013.

[27] D. Jiang, D. Zhuang, J. Fu, Y. Huang, and K. Wen, "Bioenergy potential from crop residues in China: Availability and distribution," *Renew. Sustain. Energy Rev.*, vol. 16, no. 3, pp. 1377–1382, Apr. 2012.

[28] P. Purohit and A. Michaelowa, "CDM potential of bagasse cogeneration in India," *Energy Policy*, vol. 35, no. 10, pp. 4779–4798, Oct. 2007.

[29] AgriFood Consulting, "Rice Value Chain Study: Cambodia." [Online]. Available: http://www.agrifoodconsulting.com/ai/dmdocuments/Project%20Reports/Rice%20Value%20Chain/Rice%20Value%20Chain%20Study%20Cambodia.pdf. [Accessed: 02-Jan-2014].

[30] "Husk Power Systems." [Online]. Available: http://www.huskpowersystems.com/innerPage.php?pageT=Community%20Impact&page_id=81. [Accessed: 02-Jan-2014].

[31] "How to make electricity from rice husk | Grace Boyle | Independent Editor's choice Blogs." [Online]. Available: http://blogs.independent.co.uk/2010/12/10/how-to-make-electricity-from-rice-husk/. [Accessed: 02-Jan-2014].

[32] B.N. Kapur, "Diagnostic Study Report of Rice Milling Industry at Karnal," 2003. [Online]. Available: http://www.dcmsme.gov.in/schemes/rice_milling.pdf. [Accessed: 02-Jan-2014].

[33] R. Samson, T. Helwig, D. Stohl, A. De Maio, P. Duxbury, T. Mendoza, and A. Elepano, *Strategies for enhancing biomass energy utilization in the Philippines*. National Renewable Energy Laboratory, 2001.

[34] Office of the Cane and Sugar Board (OCSB), "List of rice mills in Thailand." [Online]. Available: http://www.ocsb.go.th/upload/download/uploadfile/23-6589.pdf. [Accessed: 02-Jan-2014].

[35] "List of sugar mills | SRA." [Online]. Available: http://www.sra.gov.ph/menu_pdf/list%20of%20sugar%20mills.pdf. [Accessed: 02-Jan-2014].

[36] S. P. Singh, "Performance of Sugar Mills in Uttar Pradesh by Ownership, Size and Location," *Prajnan J. Of*, 2007.

[37] S. Zafar and P. Dahlen, "Biomass Resources for CHP Applications in Southeast Asia."

[38] Indian Sugar Mills Association, "State-wise list of sugar mills having Cogeneration." [Online]. Available: http://www.indiansugar.com/PDFS/Cogenerators.pdf. [Accessed: 02-Jan-2014].

[39] Pinta, François and Fomete, Timothée, "Filière bois au Cameroun : vers une gestion durable des forêts et une transformation industrielle performante ?," *Bois For. Trop.*, vol. 3, no. 281, 2004.

[40] S. R. Bello and Y. Mijinyawa, "Assessment of injuries in small scale sawmill industry of south western Nigeria," *Agric. Eng. Int. CIGR J.*, vol. 12, no. 1, 2010.

[41] K. Senelwa and R. E. . Sims, "Opportunities for small scale biomass-electricity systems in Kenya," *Biomass Bioenergy*, vol. 17, no. 3, pp. 239–255, Sep. 1999.

[42] Hasan, M., "The Indonesian wood panel industry," *An international journal of forestry and forest industries*, vol. 42, no. 167, 1991.

Appendix 1 : Available agricultural residues by continent and potential power generation

South-East Asia	*crop (tons)*	*Crop to residue ratio*	*residue (tons)*	*available residues for power generation (tons)*	*Power generation (kWh)*
Rice, paddy	201 009 657	1,0	201 009 657	30 151 449	15 075 724 275
Sugar cane	154 888 830	0,1	15 488 883	2 323 332	1 161 666 225
Cassava[4]	62 121 750	0,0	0	0	0
Maize	36 994 210	2,0	73 988 420	11 098 263	5 549 131 500
Total	**584 726 864**		**290 486 960**	**43 573 044**	**21 786 522 000**

Africa					
Cassava	121 661 234	0,0	0	0	0
Sugar cane	89 594 253	0,1	8 959 425	1 343 914	671 956 898
Maize	63 580 236	2,0	127 160 472	19 074 071	9 537 035 400
Rice, paddy	22 977 124	1,0	22 977 124	3 446 569	1 723 284 300
Total	**453 579 465**		**159 097 021**	**23 864 553**	**11 932 276 598**

South America					
Sugar cane	822 034 520	0,1	82 203 452	12 330 518	6 165 258 900
Soybeans	132 792 952	1,7	225 748 018	33 862 203	16 931 101 380
Maize	89 998 265	2,0	179 996 530	26 999 480	13 499 739 750
Cassava	31 686 404	0,0	0	0	0
Rice, paddy	23 475 874	1,0	23 475 874	3 521 381	1 760 690 513
Total	**1 186 145 116**		**511 423 874**	**76 713 581**	**38 356 790 543**

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[4] Cassava is cultivated as subsistence farming, therefore cassava residues are dispersed and not easy to use

India

Sugar cane	292 300 000	0,1	29 230 000	4 384 500	2 192 250 000
Rice, paddy	143 963 000	1,0	143 963 000	21 594 450	10 797 225 000
Wheat	80 800 000	1,1	88 880 000	13 332 000	6 666 000 000
Total	**672 639 000**		**262 073 000**	**39 310 950**	**19 655 475 000**